

Possible relationships between changes in global ice volume, geomagnetic excursions, and the eccentricity of the Earth's orbit

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ABSTRACT

A possible relationship between major changes in global ice volume, geomagnetic variations, and short-term climate cooling has been investigated through a study of climate and geomagnetic records of the past 400,000 yr. Calculations suggest that redistribution of the Earth's water mass can cause rotational instabilities that lead to magnetic excursions; these magnetic variations in turn may lead to rapid coolings through several proposed mechanisms. Such double coincidences of magnetic excursions and sudden cooling and glacial advance at times of major ice-volume changes have occurred at about 13,500, 30,000, 110,000, and 180,000 B.P. The last four and possibly five times of maximum eccentricity of the Earth's orbit were closely followed by magnetic excursions; catastrophic cooling and rapid ice buildup accompanied several of these excursions. Thus, Milankovitch cycle parameters may lead to glaciation through both insolation changes and geomagnetic effects on climate.

INTRODUCTION

Several workers have suggested a mechanism whereby changes in the distribution of the Earth's water mass, through the growth and decay of polar ice sheets, might lead to rotational instabilities and the type of core-mantle interactions that would result in fluctuations of the geomagnetic field (Olausson and Svenonius, 1975; Doake, 1977; Möerner, 1977, 1978). Doake (1977) has calculated that the changes in core energy involved are of the same order of magnitude (a rate of energy dissipation of 10^{12} W) as the estimated energy required to drive the geodynamo. An apparent correlation has been found between magnetic reversals and major changes in climate during the past few million years (Doake, 1978). However, errors in dating the magnetic-climatic fluctuations may be significant, and it is not clear in the association of magnetic events and climate change which is the cause and which is the effect.

For example, it is also possible that changes in the Earth's magnetic field could lead to changes in climate (Wollin and others, 1971). The low field strengths that can accompany times of magnetic reversals or excursions could lead to increased cosmic-ray flux. The climatic link might come through increased upper-atmosphere

ionization and cloud formation (Harrison and Prospero, 1974) and/or catastrophic depletion of atmospheric ozone (Reid and others, 1976). Furthermore, Bucha (1976a, 1976b) has proposed that changes in magnetic intensity and pole position could affect atmospheric pressure at the poles and lead to changes in general atmospheric circulation. These conditions could ultimately lead to increased high-altitude cloudiness, increased precipitation in middle latitudes, and perhaps to the initiation of subpolar snow fields (Bucha, 1976b; Fairbridge, 1977).

If these recent suggestions are correct, then a correlation should exist in the geologic record between rapid, large-scale changes in global ice volume (and sea level) on one hand and excursions of the Earth's magnetic field on the other. Furthermore, if magnetic fluctuations are a cause of climatic cooling, then short-term magnetic excursions should also coincide with short phases of cool climate, rapid ice growth, and glacial advance (Fig. 1).

CLIMATIC AND MAGNETIC RECORDS

A first step in this problem is to examine the climatic and geomagnetic records of the past several hundred-thousand years in

search of evidence for double coincidences of major ice and/or water redistributions, magnetic excursions, and rapid short-term coolings. One such double coincidence at the time of the Gothenburg magnetic excursion at about 13,500 B.P. has been proposed by Fairbridge (1977). This event came at about the midpoint of the rapid melting of the latest Pleistocene ice sheets in the Northern Hemisphere. The melting

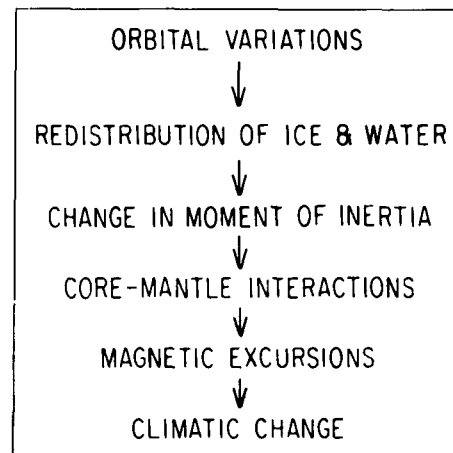


Figure 1. Diagram of possible relationships between orbital variations (Milankovitch cycle), redistribution of global water mass, changes in Earth's moment of inertia, magnetic excursions, and short-term climate change.

and water-mass redistribution were probably induced by Milankovitch insolation parameters (Kukla, 1975) and may have led to changes in the Earth's rotation, which in turn led to core-mantle instabilities and magnetically induced climate change. The Gothenburg excursion seems to have coincided with a time of anomalous short-term (10^3 yr) rapid climate cooling and ice buildup. Between 14,000 and 13,000 B.P., sea level reportedly dropped more than 10 m (equivalent to glacial readvance over $\sim 2 \times 10^6$ km²; Fairbridge, 1977).

Verosub and Banerjee (1977) considered that the two geomagnetic events resting on the best-supporting evidence during the past few hundred-thousand years are the Lake Mungo excursion at about 30,000 B.P. and the Blake event at about 110,000 B.P. The Blake event, first detected in deep-sea cores, has also been reported from a long sediment core taken from Lake Biwa in Japan. Similar excursions are recorded in deeper levels of the core and estimated to date from about 180,000 B.P., the Biwa I event, and about 295,000 B.P., the Biwa II event (Kawai and others, 1972), although the excursions have been disputed by others (D. V. Kent, personal commun.). Dating of these excursions in the Lake Biwa core is based on ¹⁴C age determinations in the upper part of the core and fission-track dating of volcanic ash layers between 40 and 100 m in the

core. These age determinations have allowed construction of an age versus depth curve for the core (Yaskawa, 1974). Excursions that are believed to correlate with the Lake Biwa events have also been detected in deep-sea cores (Wollin and others, 1971; Yaskawa, 1974; Fig. 2). The magnetic events are coincident with pronounced lows in organic carbon in the Lake Biwa sediment core (Fig. 3). The decreases in organic carbon are believed to be related to periods of cool climate and low productivity of the lake (Kawai and others, 1975).

The Blake event apparently occurred at the same time as the quite sudden ice buildup and climatic cooling that immediately followed and terminated the last interglacial stage (the Eemian). Studies of the oxygen-isotope ratio in deep-sea cores (Shackleton, 1976, 1977; Johnson, 1978) and of changes in sea level recorded in tropical coral-reef terraces (Matthews, 1972) suggest that, at about 110,000 to 115,000 B.P., the level of the sea fell 60 to 70 m in less than 10,000 yr (Andrews and Mahaffy, 1976). The rate of growth of ice sheets would have been such as to produce a volume of about 28×10^6 km³ of ice (equivalent to the present Antarctic and Greenland ice sheets) in less than 10,000 yr. Climatic changes on time scales of 10^3 to 10^5 yr are now believed to be strongly modulated by changes in the Earth's orbital geometry and their effects

on the seasonal distribution of insolation (the Milankovitch insolation mechanism; Hays and others, 1976). A climatic cooling at the time of the Blake event ($\sim 110,000$ B.P.) would be predicted by the Milankovitch insolation mechanism, but the ice buildup was extremely rapid. The rapidity might be explained as a result of changes in atmospheric and oceanic circulation and precipitation resulting from geomagnetic fluctuations (Bucha, 1976a, 1976b; Fairbridge, 1977), which might act in concert with circulation changes induced by insolation variations (Johnson and McClure, 1976).

The magnetic event at about 30,000 B.P., the Lake Mungo excursion, is also associated with a time of apparent rapid cooling immediately following a major climatic warming and retreat of ice (the Plum Point Interstade in North America and the Stillfried-B Interstade in Europe). This brief interval of warming ($< 5,000$ yr) is not well recorded in most deep-sea cores, and hence the extent of warming is controversial (Fig. 4). However, the sea was within 40 m of its present level at about 30,000 B.P. (Chappell and Veeh, 1978) (although some authors suggest sea levels as high as -10 m mean sea level; Blackwelder and others, 1979), and climate in some middle latitude areas was similar to that of the Holocene (Sirkin, 1977). Radiocarbon dating and pollen analyses of near-shore marine deposits in the northeastern

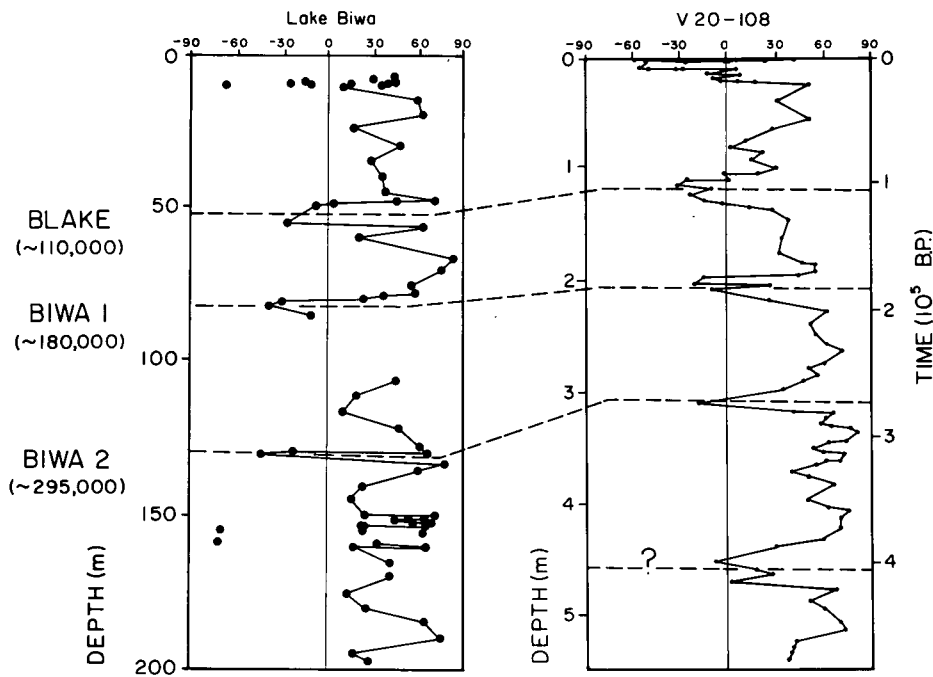


Figure 2. (A) Magnetic inclination plotted against depth in Lake Biwa core, results of preliminary measurements of samples taken at 5-m intervals (Yaskawa, 1974). Estimated dates of excursions based on fission-track dating of volcanic ash layers are given at left. (B) Magnetic inclination plotted against depth in deep-sea core V20-108 (Wollin and others, 1971). Time scale at right is based on assumption of constant sedimentation rates between top of core (zero age) and Brunhes-Matuyama boundary at about 7.5 m depth in core.

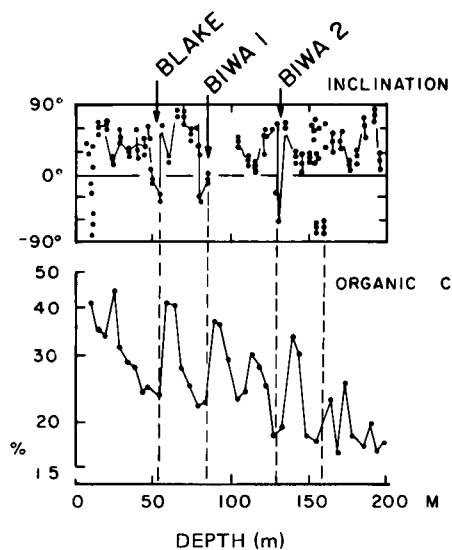


Figure 3. Magnetic inclination and percent organic carbon plotted against depth in Lake Biwa sediment core. Positions of Blake, Biwa I, and Biwa II magnetic events are shown by arrows (Kawai, 1974).

United States point to a very rapid cooling just after 28,000 B.P.; temperate vegetation was replaced by boreal-type forests within a few hundred years (Rampino and Sanders, 1976; Sirkin, 1977). Sea level may have dropped to more than -100 m mean sea level by 18,000 B.P. (Dillon and Oldale, 1978), an average of $>6\text{m}/1,000\text{ yr}$. These rapid rates of change in global climate are similar to those at the time of the Blake event.

The Biwa I magnetic excursion, estimated at about 180,000 B.P., also appears to have coincided with a time of rapid growth of ice sheets as indicated by oxygen-isotope curves of deep-sea sediment cores (Fig. 4). Furthermore, the Biwa I event took place when Milankovitch insolation parameters would suggest growth of global ice sheets. However, the expansion of ice sheets was again very rapid (as seen in oxygen-isotope curves), and sub-Antarctic sea-surface temperatures are reported to have declines about 2°C at this time. The interval is also marked by the last appearance of the diatom *Hemidiscus karstenii* in the sub-Antarctic (Burckle and others, 1978). Such extinctions have previously been related to magnetic reversals (Hays, 1971) and may be a result of the environmental stress directly associated with the magnetic field fluctuations and/or a result of the climatic cooling. It is stressed here that these magnetic events have not been detected in the same deep-sea cores that were used for isotopic studies, so that correlation of the climate curve with the magnetic events is indirect. However, events of a few thousand years' duration are unlikely to be shown in most deep-sea cores as a result of mixing processes on the ocean floor.

The time of the Biwa II event at about 295,000 B.P. was apparently not accompanied by rapid changes in ice volume, as indicated in oxygen-isotope studies of most deep-sea cores (Fig. 4). However, the high deposition rate shown by the Lake Biwa core ($\sim 50\text{ cm}/1,000\text{ yr}$) indicates a marked decrease in productivity, interpreted as a regional cooling at the time of the Biwa II event. A very short (a few thousand years) period of rapid growth of

ice sheets might be beyond the resolving power of most deep-sea cores. The details of the climatic changes at about 295,000 B.P. are not well known at present.

An as yet unnamed magnetic excursion that has been detected in deep-sea cores and dated at about 400,000 B.P. also apparently correlates with a time of rapid ice growth and immediately follows a time of major melting of Northern Hemisphere ice sheets (Figs. 2, 4). Indications of such an event are also found in the Lake Biwa core (Fig. 2). Although not well documented at present, this coincidence adds further support to the association of climate and geomagnetism proposed here.

DISCUSSION

Of course, coincidences of events, such as changes in global ice volume, magnetic excursions, and short-term rapid glaciations and climatic coolings, do not prove cause-and-effect relationships. The relationships proposed here must at this time be considered highly speculative. Other magnetic excursions that have been reported apparently did not occur at the same times as major ice-volume changes and rapid coolings recorded in oxygen-isotope curves of deep-sea cores (Verosub and Banerjee, 1977). However, many of the reported excursions are poorly dated, and the reality of several reported magnetic events has been questioned. The record preserved in many deep-sea cores may have poor resolution of events shorter than a few thousand years as a result of slow rates of deposition, bioturbation, and/or dissolution of calcium carbonate. Most deep-sea cores, therefore, are not suitable for study of very short-term magnetic excursions and climatic events. Future work on sediments with higher rates of deposition in lakes and/or anaerobic basins promises to resolve these problems.

Eccentricity, Climate, and the Magnetic Field

It is notable that the last four, and possibly five, times of maximum eccentricity of the Earth's orbit were apparently

closely followed by magnetic excursions (Fig. 4). Eccentricity maxima appear to coincide with brief periods (10^4 yr) of minimum ice cover (the interglacial periods) that follow rapid melting of Northern Hemisphere ice (Hays and others, 1976). Such rapid changes in water-mass distribution might lead to the subsequent magnetic excursions (Doake, 1977).

Furthermore, Wollin and others (1977, 1978) have argued that the eccentricity of the Earth's orbit directly modulates the geomagnetic field through the resulting variations in precession. Kent and Opdyke (1977) reported a relationship between geomagnetic field strength and a 41,000-yr cycle of the Earth's tilt; the entire question of modulation of the Earth's magnetic field by orbital parameters is at present being debated. Therefore, the excursions might be a result of orbital variations that directly affect core-mantle dynamics and/or produce the changes in global ice volume and mass distribution that could affect the Earth's rotation and thus set up instabilities in the core (Fig. 5). Some excursions (for example, the Lake Mungo excursion) were not associated with a maximum of orbital eccentricity, but they do seem to have followed times of rapid ice melting.

It appears that if the excursion occurs at an unfavorable time in the Milankovitch insolation cycle (as with the 13,500-B.P. Gothenburg excursion), then only a brief glacial readvance is observed; but if the geomagnetic trigger occurs at a "sensitive"

Figure 4. Record of oxygen-isotope variations during past 475,000 yr in sub-Antarctic deep-sea cores (Hays and others, 1976). Low values of δO^{18} indicate small ice volumes; high δO^{18} values indicate large ice volumes. Times of five reasonably well-established magnetic excursions discussed here are shown by solid arrows. (These excursions were not detected in deep-sea cores used to construct record of δO^{18} .) Time of a sixth magnetic excursion, detected in some deep-sea cores and unnamed at present, is shown by dashed arrow. Dotted line is plot of eccentricity of Earth's orbit.

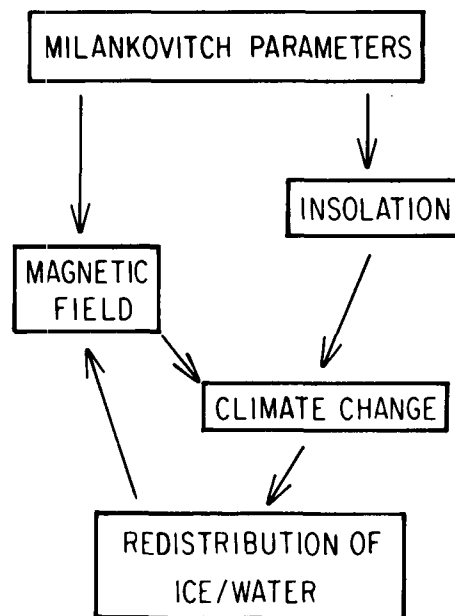
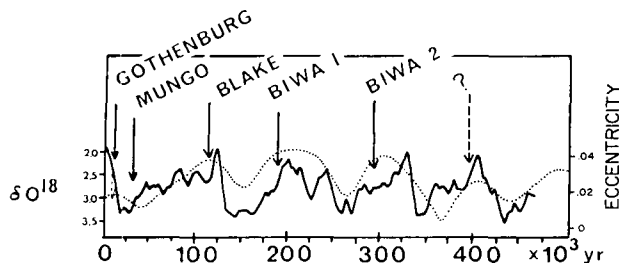


Figure 5. Diagram of possible relationships between Milankovitch cycle of orbital parameters and climatic change through intermediaries of insolation changes and fluctuations of geomagnetic field.

phase of the Milankovitch cycle, then a full glacial stage may be initiated.

If these factors are taken into consideration, the catastrophic cooling episodes that may have ushered in the last three or four major glacial stages could have been triggered by magnetic excursions that were the direct or indirect result of astronomical forcings. If these relationships are correct, then the Milankovitch insolation hypothesis for glacial-interglacial cycles may be only a partial solution to the problem of glacial initiation. The insolation effects and related feedback mechanisms, such as changes in oceanic and atmospheric circulation and global albedo, might be reinforced by the changes in atmospheric-oceanic circulation and climatic cooling that have been proposed to accompany magnetic excursions.

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